THERMO-VACUUM TEST CHAMBER DEVELOPMENT FOR AIRBORNE AND SPACE EQUIPMENT TESTING IN SIMULATED EXTREME CONDITIONS

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Abstract

The Institute of Aerospace Engineering, Brno University of Technology developed a unique thermo-vacuum test facility to simulate extreme aerospace environmental conditions. Even though originally developed for space technology Qualification tests, the know-how can be used to test airborne equipment in laboratory to develop and certify new prototypes under civil or military aviation regulations. Moreover, the experimental thermo-vacuum chamber can be used for research and development of space technologies and its testing in different simulated space environments.

The innovative tailor-made thermo-vacuum chamber presented here was designed to enable test procedures in simulated Martian atmospheric conditions (vacuum of 50 Pa absolute, temperatures up to −125 °C and pure CO_2 environment of 1000 Pa absolute). The vacuum tightness of the chamber, the deep cooling of the tested sample under a vacuum environment, the thermal insulations or the heat transfer paths had to be precisely considered. The verification tests of the facility design then proved excellent performance and viability for future technology modifications.

This paper reflects the market needs to test airborne and space equipment in different vacuum-cryogenic and thermally controlled extreme conditions.

1 Airborne and Space Equipment Testing

Avionics equipment and space technologies have to meet particular requirements to be used in operation on-board. Therefore, all the devices, systems and installations are tested in laboratories, especially to meet the operational environmental conditions.

In aviation, the level of environmental condition requirements and related test procedures are specified in commercial and military certification standards, e.g. RTCA DO-160, EUROCAE ED-14, MIL-STD or SAE Aerospace Standards. To get the Type Certificate approval that allows the airborne equipment to be used in aviation, the criteria and appropriate standard requirements have to be met.

In space industry, the equipment is rated based on the technology maturity for use in a harsh space environment. The ISO 16290 defines the Technology Readiness Level (TRL1 to TRL9) scale and criteria for assessment. TRL1 level represents the basic physical principles observed. On the contrary TRL9 keeps status of “flight proven” equipment through successful mission operations. The promotion from TRL4 to TRL7 are based only on a critical function verification in a laboratory simulated relevant and operational space environment.

These all points the necessity to test and certify the airborne and space equipment in simulated extreme environmental conditions.

2 Test Campaign Requirements Definition

2.1 Space-technology Specimen

The Miniaturized Heat Switch (MHS) is the unique technology under the development of the Italian company Arescosmo (formerly Aero Sekur) for European Space Agency (ESA). The MHS is the automatic thermal control device which is going to be implemented in systems of space probes or satellites. The Switch has to keep operating temperatures inside of an isolated box with electronics in predefined limits, changing the heat transfer rate between the inner satellite and outer space environment.

The Switch has two interfaces and an actuator in between, as shown in Fig. 1. The Cold interface (CI) mounted to the heat sink radiates the excessive heat to the outer space environment. The Hot interface (HI) is mounted to the source of heat – the electronics. If the HI temperature increases above the predefined limit, the actuator closes the thermal contact. On the contrary, if the HI temperature decreases below the limit, the heat path is disconnected, and the MHS creates thermal insulation for the equipment. The actuator motion is automatically controlled by thermo-physical properties of paraffin without the necessity of external power supply.

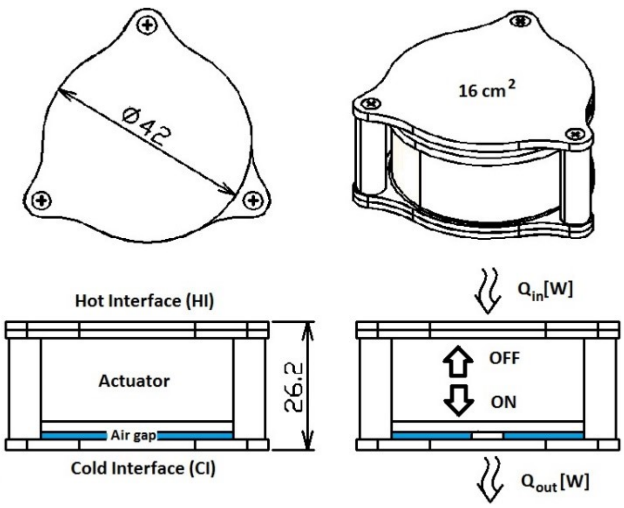

Fig. 1. Space Heat Switch specimen (dimensions in mm).

The technology of the paraffin actuated heat switch had already been tested decades ago. However, the switches had much lower conductivity and were bigger in size.

An early wax system for thermal control has already been used on the Lunar Roving Vehicle on Apollo 15 [1], NASA later developed a wax actuated heat switch for Mars that had been tested on the Mars Exploration Rover Mission [2]; [3].

The presented Heat Switch, Fig. 1, should overcome in all aspects the performance of its predecessors.

2.2 Experimental Facility Performance Requirements to Test the Heat Switch

The targeted Qualification test of the Heat Switch technology to prove its design and performance in simulated Martian conditions, defines the requirements for the testing facility design.

The essential environmental conditions have to meet a level of vacuum up to 50 Pa absolute and pure CO_2 pressure of 1000 Pa absolute. The temperatures available at the Switch interfaces have to be in the range from – 125 °C to + 60 °C and the experimental facility has to ensure application of up to 10 W at the HI. The experimental facility has to allow to measure and regulate all these critical conditions, as specified in Tab. 1.

Tab. 1. Thermo-vacuum chamber performance requirements.

Environmental conditions:			
Vacuum pressure	50		Pa
Mars environment (CO_2)	50	1000	Pa
Heat Switch contact conditions:			
HI temperature	-55	60	°C
CI temperature	-125	50	°C
Heat flux applied at HI	0	10	W
Measurement ranges:			
Thermal conductivity	0,01	1	W/K

The Qualification test campaign has to determine whether or not the MHS is switching within the specified temperature range, Fig. 2, as well as to measure the ON and OFF thermal conductivity under different presumed conditions, Fig. 3.

The first set of conditions was to keep four different constant temperatures (− 15; 0; 15 and 30 °C) on the CI and simultaneously to apply predefined heat loads up to 10 W at the HI, Fig. 2.

The second set of conditions was to apply temperature cycles from – 15 °C to + 30 °C on the CI and simultaneously to heat up the HI by 10 W of power, Fig. 3.

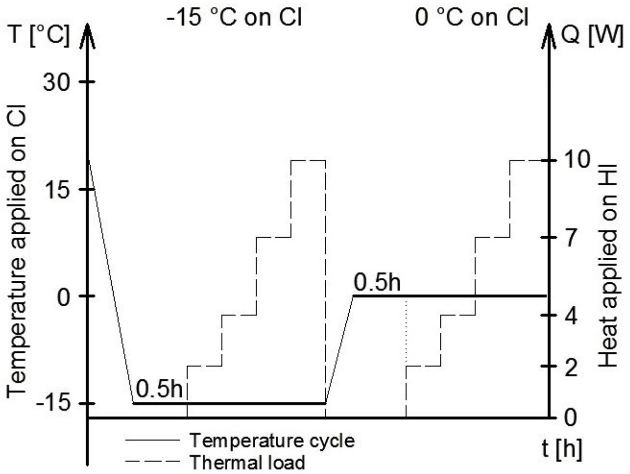

Fig. 2. Test procedure No. 1.

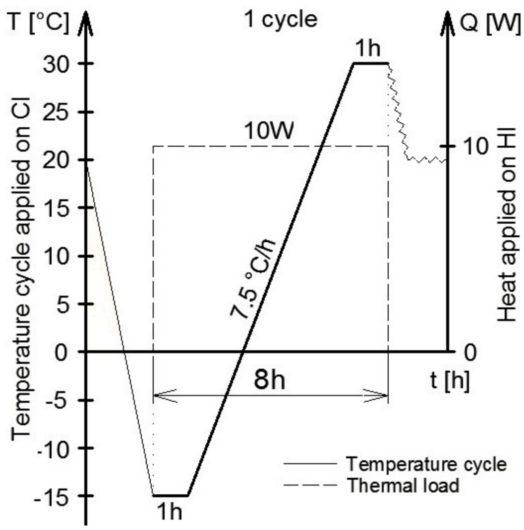

Fig. 3. Test procedure No. 2.

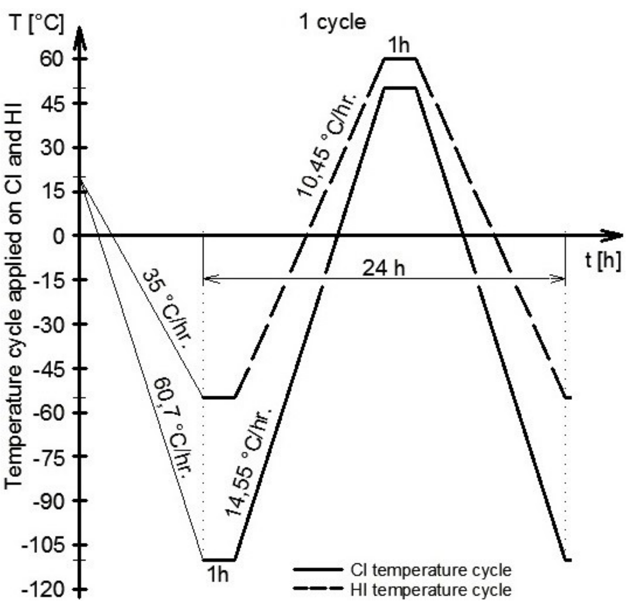

Fig. 4. Test procedure No. 3.

The third set of conditions was considered mainly to simulate a day/night cycle on Mars by applying temperature cycles on both the switch interfaces within 24 hours; on CI: − 110 °C to + 50 °C and on HI: − 55 °C to + 60 °C, as shown in Fig. 4.

The test campaign defined strict demands for the test chamber development. Except achieving the extreme temperatures and low pressures, there were other requirements: to measure and regulate temperatures independently on both the MHS interfaces, to evaluate heat transfer through the Heat Switch and to measure the pressure inside of the vacuum chamber.

3 Thermo-vacuum Chamber Development

To fulfil the test campaign requirements, two options were considered: to modify a commercial climatic chamber or to develop a new tailor-made testing facility.

There had been identified commercial facilities which were suitable for modification to perform desired tests. However, these facilities were built specifically for other purposes, and therefore, the extent of changes to meet the requirements of the MHS test campaign would be significant. Moreover, the calibration tests would have to be performed anyway. All these aspects would mean large expenses.

The preferable decision was to design a new test facility based on the simplest technologies possible to reduce initial and operating costs while the test requirements would be met.

The experimental facility for MHS Qualification tests consists of a thermo-vacuum chamber and its supply and control systems to create the extreme space conditions of Mars.

3.1 Thermo-vacuum Chamber Design

According to the Heat Switch predefined performance, the research aimed to develop an innovative but simple experimental thermo-vacuum test chamber to simulate Martian atmospheric conditions.

The chamber has to withstand a vacuum of 50 Pa absolute and temperatures down to

– 125 °C. Consequently, the vacuum tightness of the chamber, the deep cooling of the specimen under a vacuum environment, the thermal insulations or the heat transfer paths had to be precisely considered.

An important decision was to use the liquid nitrogen (LIN) as the most appropriate cooling medium and the copper rods for the heat transfer to outside of the chamber.

Selection of materials:

Three materials were chosen with respect to the market commonality and intended application in the thermo-vacuum chamber construction: Stainless steel 314L was used for the chamber walls, predominantly loaded by external pressure; Copper OFHC was used for components acting as a heat path and Teflon (PTFE) as a thermal contact insulator suitable for the vacuum environment. Additionally, Polystyrene foam was used outside of the chamber as the LIN tanks thermal insulation, as shown in Fig. 5.

Cooling:

Liquid nitrogen satisfies both the extreme low temperature limits and easy operation in comparison to the other cryogenic liquids.

The heat transfer copper rods, which are going through the main flanges of the chamber, Fig. 5, were designed to cool down both interfaces through thermal conductivity. This idea fits to the safe low-cost solution.

The layout also satisfies the requirement to cool both specimen interfaces independently. The HI copper rod is connected to the HI by four copper belts to facilitate the thermal contraction of the CI copper rod that supports the specimen assembly completely.

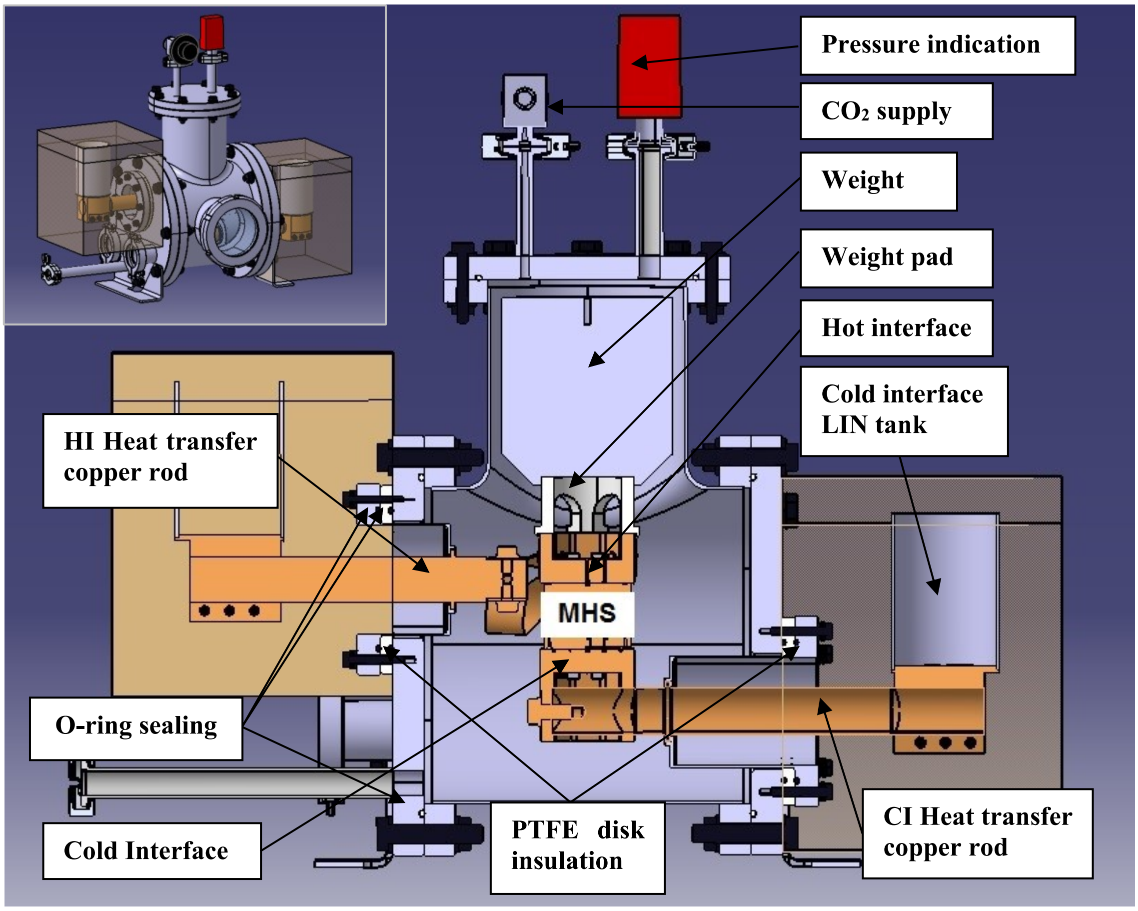

Fig. 5. Thermo-vacuum test chamber cross-section (isometric view in the upper - left corner); Inner volume: 5.5 dm^3; Dimensions l/w/h: 530/344/393 mm. *[4]*

Vacuum tightness in the cryogenic environment:

Special stainless-steel cylinders with a wall thickness of 1 mm acting as heat resistors were developed to ensure a vacuum tightness close to deeply cooled rods going through the chamber walls where the rubber sealing ceases to function in temperatures below – 40 °C. These cylinders held the copper rods by solder joint and were isolated by PTFE disks from the chamber walls. Additionally, in this case, the common rubber O-rings were replaced by the PTFE ones.

The solder joints between copper and steel were critical to the chamber design due to the risk of cracking under high loads. The joint stresses result from the tight connection of two greatly thermally loaded materials with different expansion coefficients and alike from the mechanical loads caused by the outer pressure as well as by the heat transfer assembly weight (including the weight component placed above the MHS).

Two critical points had to be verified:

1) Soldered joints between stainless steel chamber flanges and the copper rods for thermal conducting - will be the joint vacuum-tight and withstand a load of 10 kg at −125 °C of the CI?
2) Will the special stainless steel cylinders and PTFE disks isolate efficiently the deeply cooled copper rods from O-rings sealing used in the grooves of all flanges?

Thermal transfer path design:

The heat power is added to the HI above the specimen, passing down through the Heat Switch to the CI and leaving the vacuum chamber by the CI copper rod, as can be observed in Fig. 5. During the measurements when the amount of heat is relevant, the copper belts are disconnected and the added heat pass only through the specimen. The Weight of 10 kg standing on the Weight pad (made of PTFE for thermal insulation) has to create pressure between the surface contacts in the tested specimen assembly, improving the thermal contact conditions.

The chamber walls incorporate two maintenance and inspection flanges; upper flange is intended for manipulation with the Weight, the front window flange for manipulation with the specimen and visual control of the conditions during testing. The chamber-wall flanges further incorporate smaller KF flanges to accommodate vacuum feed-throughs, pressure gauge, CO_2 and vacuum hoses.

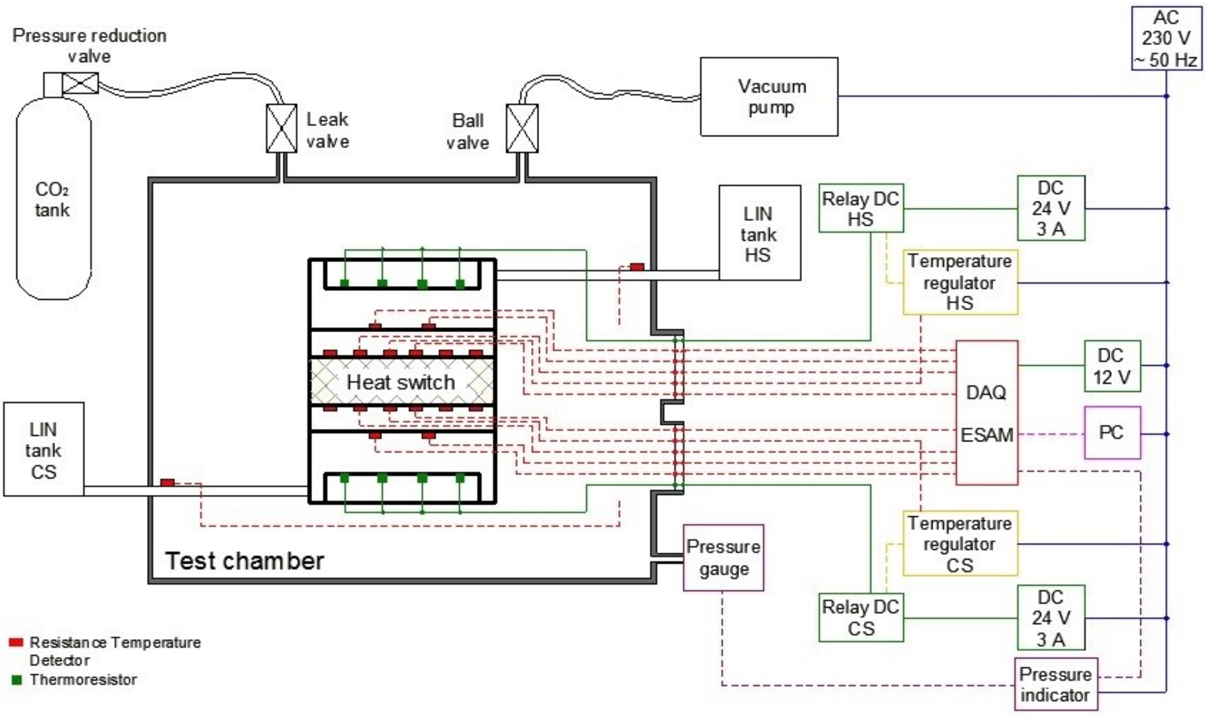

Fig. 6. Vacuum chamber supply systems design. [5]

The thermo-vacuum chamber was developed gradually. In the first step, the initial chamber was designed and manufactured immediately. In the second step after the chamber assembly, several initial tests to verify its performance were done. The facility was then several times modified step by step to fulfil all the requirements. Therefore, a decision that the chamber would be of modular design was beneficial.

3.2 Vacuum Chamber Supply and Control Systems Design

The following external supply systems for the vacuum chamber were designed to fulfil all the requirements for MHS testing, consisting of supply systems for cooling, heating, vacuum and CO_2 environmental regulation and data acquisition system to store the measured temperature and pressure. System scheme draft can be seen in Fig. 6. The complete systems overview and specification of each component is listed in Tab. 2.

Tab. 2. List of supply system components. [5]

Vacuum system:
Ball valve (IBV16MKS NW16)
Vacuum pump
System of CO_2 supply:
CO_2 tank (8.2 dm^3, 200 bar - 200 x 10^5 Pa)
Leak valve (LV10K Fine Control Leak Valve)
Reduction valve (200 bar / 2 bar)
Pressure measuring devices:
Active Pirani gauge (APG 100 XM NW16)
Active Digital Controller (ADC: MkII enhanced version)
Cooling system:
Liquid nitrogen (LIN: - 196 °C)
Tank for liquid nitrogen storage (Dewar bottle)
Automatically controlled heating system:
DC relay (CRYDOM D4D07)
Temperature Controllers (Ht40P – TE-K0R-000)
Resistors (R 8R TO220 35W 1% HITANO)
DC power supply
Temperature measuring devices:
Temperature probes (Pt 100: P0K1-202-3FW) *
Feed-throughs (D-sub 2 x 9 pin / KF40)
Data acquisition system:
ESAM Traveller 1CF (32 Channels) version 2.5

* Three-wire line configuration routing was applied to the temperature sensors to avoid parasitic heat sources/ leaks influencing measured signals.

Heat and temperature regulation:

All in all, 18 temperature probes Pt 100 are used to measure temperatures independently on different surfaces in the heat transfer path through the specimen assembly, Fig. 6.

Temperature sensors at the CI are used for temperature semi-automatic regulation based on cooling of the CI by LIN (manually added to the CI tank) and automatically regulated reheating up to the required CI temperature by a set of four thermoresistors. The heat power is supplied to the HI by four resistors equally.

The measured temperature signals and heat power are transferred through the chamber walls by vacuum feed-throughs with D-sub 2 x 9 pin connectors.

The thermal conductivity of the Heat Switch is then evaluated from the heat power added to HI divided by a temperature difference measured on both specimen interfaces.

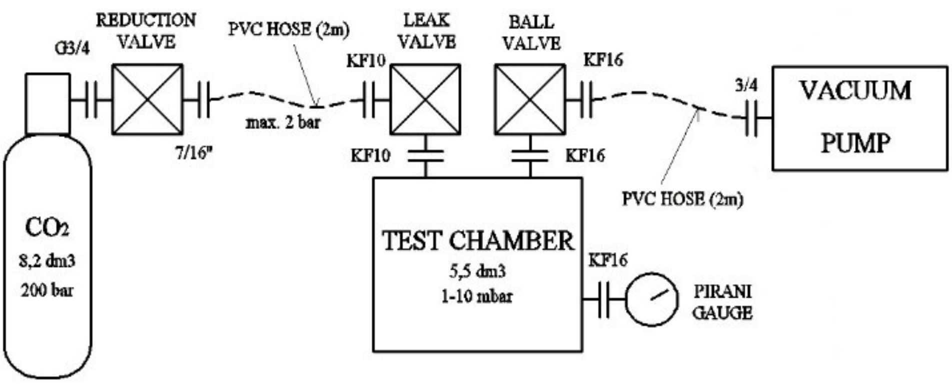

Fig. 7. Vacuum and CO_2 supply system design. [5]

System of vacuum and CO_2 supply:
A regulation of vacuum and CO_2 environment was originally designed to be manual with continuous supply of CO_2 gas into low pressure environment while the vacuum pump is running and vacuuming the test chamber.

CO_2 gas is stored in a conventional CO_2 tank and is supplied through the Reduction valve, which decreases the pressure from original 200 bar (200 x 10^5 Pa) of the full CO_2 tank to min. 2 bar (2 x 10^5 Pa) pressure for the Leak valve. The Leak valve then feeds the gas into the vacuum chamber low-pressure environment to create the required conditions of Martian atmosphere. The pressure control system regulation is provided manually based on the appropriate test procedure needs. The final layout of the pressure control system can be seen in Fig. 7.

The measured signals from temperature probes and pressure gauge were processed in the data acquisition system and stored for the specimen thermal conductivity evaluation.

4 Results - Validation of the Experimental Testing Facility

During the first performed tests the initial chamber design endured the most extreme assumed conditions and was therefore proved to follow the prescribed chamber configuration calibration procedure. The first limitation came out due to the CO_2 solidification that was predicted to appear below the temperatures of roughly − 110 °C.

The calibration vacuum-tightness test of the experimental chamber showed that the pressure increased from the initial value of 220 Pa absolute to 450 Pa absolute within 16.5 hours at ambient temperatures, red curve in Fig. 8. A similar result was obtained in the test case of precooled copper interfaces down to − 140 °C, blue curve in Fig. 8. These tightness test results proved an excellent chamber design, particularly the tightness of the soldered joints and thermal insulation of the rubber sealing.

Moreover, according to the tightness test achievement, the pressure-vacuum regulation was changed from preliminary continuous flow set up to non-continuous flow control of CO_2 to reduce the complexity of the regulation and costs (the chamber is now fully enclosed by valves during each test procedure).

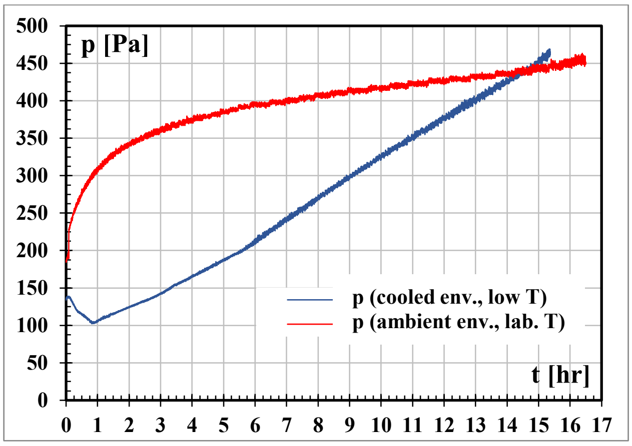

Fig. 8. Chamber vacuum-tightness calibration test. [5]

The temperature probes Pt 100 are highly accurate sensors. However, signals sent through the wiring can be influenced by supplied thermal loads that change the wire resistance and alike by additional electrical resistance in connectors that interconnect the wiring on both sides of the chamber walls. Both signal distortions were solved by adoption of 3-wire line configuration layout that compensates the possible changes in resistance. To reach sufficient temperature sensing stability, more probes were used at each desired surface and the average accuracy achieved was ± 0.1 °C.

The pressure sensing accuracy ± 30 % for pressures lower than 100 Pa is the usual value given by the manufacturer.

Tab. 3. Vacuum chamber calibration test results.

Pressure increase rate (lab. T = 21 °C)	15	Pa/hr.
Pressure increase rate (low T = −140 °C)*	25	Pa/hr.
Temperature sensing accuracy	± 0,1	°C
Pressure sensing accuracy	± 30	%
Thermal conductivity evaluation accuracy	± 5 %	W/K

* possible to see the solidification of CO_2 in pressure drop of the blue curve in Fig. 8.

4.1 Properties of the Developed Testing Facility Evaluation

Modifications to the inner as well as the outer configuration of the initial chamber design were successively made during the validation test campaign.

A reduction of thermal contact resistance by implementing graphite foils between the flat surface contacts was one of those improvements.

Insulation layers were adopted around the thermally loaded copper interfaces and MHS specimen, consisting of Mylar foil-foam-foil sandwich to diminish the heat leaks by convection and radiation. The outer Mylar foil layer shields the tested assembly from chamber walls radiation due to high steel emissivity.

Tab. 4. The best achieved performance of current experimental facility design.

Environmental conditions:			
Vacuum pressure	$5x10^{-3}$		Pa
Gas environment (N_2, Ar, Ne, Kr)	10	10^5	Pa
Heat switch contact conditions:			
HI temperature	-100	100	°C
CI temperature	-140	100	°C
Heat flux applied at HI	0	15	W
Measurement ranges:			
Thermal conductivity	0,005	2	W/K

All the achieved limits of the current experimental facility exceed the minimum required values for the Heat Switch testing, compare Tab. 1 and Tab. 4.

The vacuum chamber reached outstanding performance in the pressure tightness and the high level of thermal insulation. The modular facility design and its ability to be re-configured regarding a wide range of different required conditions promote the chamber design success the most.

4.2 Possible new design of testing facility – achievable properties

The capability of the facility modularity could also be simply used in the future to test a variety of the space or airborne equipment in different simulated environments.

The possible considered new design of the testing facility would be based on the current technology & equipment used, achievable properties of such a system are in Tab. 5. In this case, to adapt variety of test samples, the internal modification of the interfaces would have to be done.

For future applications, the use of extended automatic regulation can be considered, for example, the regulation of the cooling medium dosing or pressure-gas environment re-setting up by automatic valve control.

Tab. 5. Achievable properties of the new tailor-made experimental testing facility.

The volume of the vacuum chamber	50		dm^3
Pressure	10^{-4}	10^5	Pa
Gas environment (N_2, Ar, He, Ne, Kr,...)*	10	10^5	Pa
Temperatures	-150	150	°C
Electric signals (D-sub 2x9 pin)	unlimited		-
Heat power (max.)	72		W
Data acquisition system (max.)	72 channels		

* not O_2, H_2, flammable or dangerous gases or gases under special regulations; corrosive gases acceptable after material compliance check.

The know-how can be used to allow performing the following environmental certification tests according to RTCA DO-160, Tab. 6.

Tab. 6. Allowable environmental tests of airborne equipment according to RTCA DO-160.

Conditions	Sections*
Temperature and Altitude	4.0
Low temperatures	4.5.1
High temperatures	4.5.2 & .3
In-Flight Loss of Cooling	4.5.4
Altitude	4.6.1
Decompression	4.6.2
Overpressure	4.6.3
Temperature variation	5.0
Humidity	6.0

* Applicable for all test procedures according to different assigned category of equipment.

5 Conclusions

The presented thermo-vacuum test facility design proved to have exceptional viability and endurance for further evolution.

Even though developed for unique and new space technology – the Heat Switch – testing, the experience and the test chamber itself can be applied to many various fields, one of which may be aeronautics.

It can provide an excellent opportunity for the industry and research partners to test the equipment and avionics in simulated extreme environmental conditions under civil or military aviation regulations (RTCA/DO-160, MIL-STD, etc.) or to promote the maturity of space technologies in the research & development projects from TRL4 up to TRL6, and possibly TRL7.

The introduced new test facility was designed based on the simplest technologies possible to reduce initial and operating costs but able to meet all the environmental test requirements. The development resulted in an original and tailor-made test facility consisting of the thermo-vacuum chamber and external supply systems.

The vacuum chamber modular design enabled to make several remarkable modifications throughout its performance verification test campaign. Successful facility calibration test results were approved by ESA.

The experimental facility development is the first essential step to perform the final Qualification tests of the Miniaturized Heat Switch technology to prove its design and performance in simulated Martian conditions.

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